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TECHNICAL REPORT ARBRL-TR-2031

AIR DEFENSE GUN FIRE CONTROL SYSTEM PERFORMANCE WITH A BIAS PREDICTOR

Pak T. Yip

December 1977

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USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
USA BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TECHNICAL REPORT ARBRL-TR-2031	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AIR DEFENSE GUN FIRE CONTROL SYSTEM PERFORMANCE WITH A BIAS PREDICTOR		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) PAK T. YIP		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L662618AH80
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Materiel Development & Readiness Command 5001 Eisenhower Avenue Alexandria, VA 22333		12. REPORT DATE DECEMBER 1977 13. NUMBER OF PAGES 34
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Gun Air Defense Fire Control System
Kalman filter
Probability of hit
FACTS
Bias Predictor

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A bias predictor was introduced to couple with a simple nine state discrete Kalman filter for solving the gun fire control problem. The performance of this system showed that an earlier and higher probability of hit can be achieved if the defended target position is known.

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I. INTRODUCTION

In general, the strategy of an attacking aircraft may consist of two major typical phases, the pre-delivery-maneuver phase followed by the weapon-delivery phase. In the pre-delivery-maneuver phase, the aircraft usually maneuvers evasively creating a highly jinking noise signal with which very poor estimation of the aircraft states can be expected. A typical estimation error profile is demonstrated in Figure 1. It is obvious that the poor state estimates, resulting from this maneuver phase, will present poor intercept prediction of either second order or first order type. However, a predictor making use of information on aircraft position, velocity and ground target location, and eliminating the estimates of aircraft acceleration and jerk might, in concept, provide more accurate prediction capability. That is, a bias predictor making use mainly of the position estimates and estimated speed of the aircraft, and the assumption of a known target position, may provide a better intercept prediction. In the weapon-delivery phase, the aircraft uses only those minimal maneuvers required to maintain target alignment. An earlier hit in this phase has normally been limited, due to the slow settling of the velocity and acceleration state estimates of the aircraft, changing from a highly jinking to a slight maneuver phase. We will attempt to use only the position and speed estimates of the aircraft and knowledge of target position to generate an intercept prediction, hoping that will help achieve earlier hits. Also, it is in this phase that we may use an appropriate model with good aerodynamic characteristics to simulate the attacking aircraft.

Therefore, this report is devoted to the study of the possibility of improving system performance by using the bias predictor for intercept prediction in the weapon-delivery phase. The extension of the idea to the aircraft prediction in the pre-delivery phase will be examined in a follow-up study.

In Section 2, a Kalman filter with an adaptive scheme for the plant noise covariance matrix is discussed. A bias predictor using aircraft aerodynamics is presented in Section 3. In Section 4, a system performance model is discussed. Finally, some results from applying the Kalman filter and the bias predictor on several passes of the FACTS* profile are summarized in Section 5.

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*"Frankford Aircraft Capability Test Study," actual flight data prepared by Frankford Arsenal, Department of the Army, Philadelphia, PA, March, 1974.

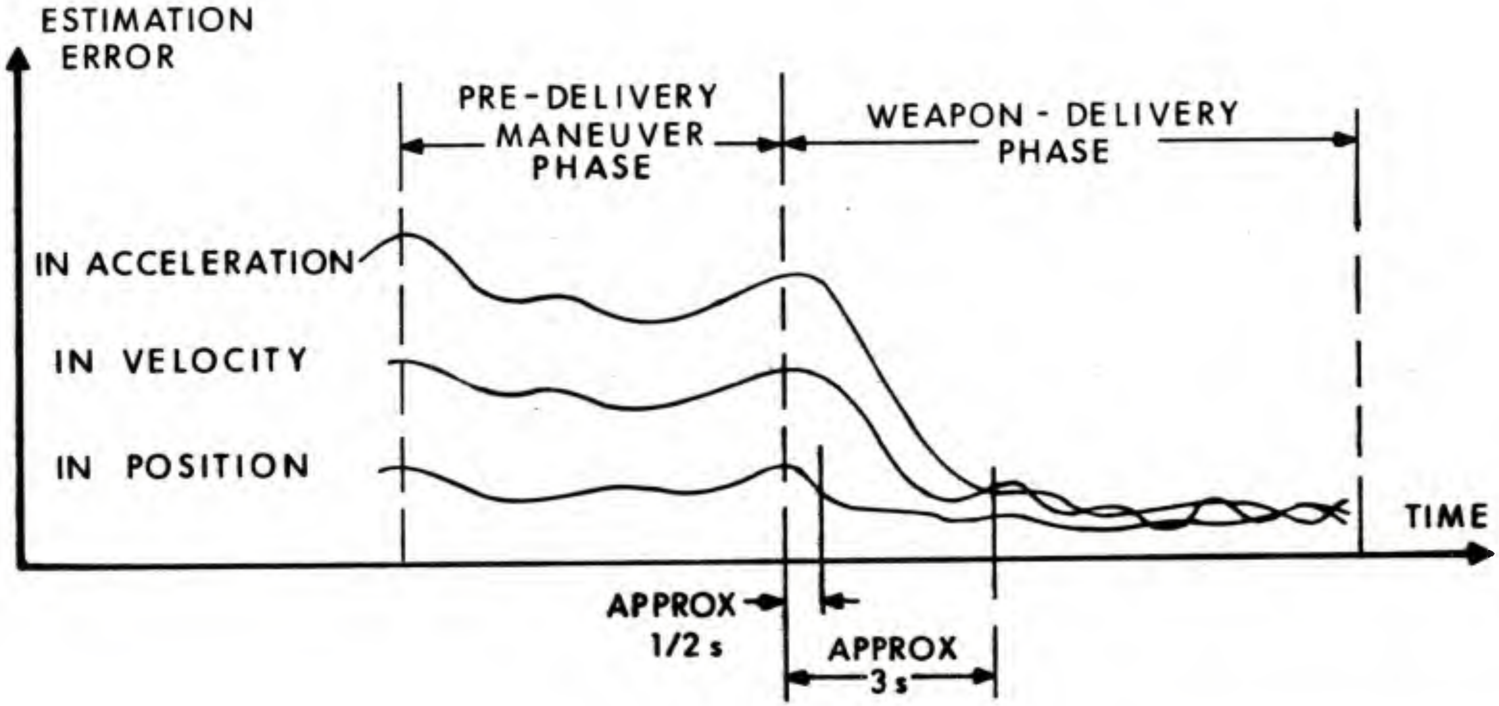

Figure 1. Typical Estimation Error Profile for Tracking an Attacking Aircraft

II. THE FILTER MODEL

A simple 9 state discrete Kalman filter was used to provide estimated aircraft states. The plant equation describing aircraft dynamics is:

$$X_{K+1} = T_{K+1,K}\, X_K + U_K$$

where X_K is the state vector at time $K\Delta t$; X_{K+1}, the state vector at time $(K+1)\Delta t$; $T_{K+1,K}$, the state transition matrix; U_K, the driving input; and Δt, the sampling time step. The estimated state equation is

$$\hat{X}_{K+1} = T_{K+1,K}\, \hat{X}_K + W_{K+1}\left(Z_{K+1} - H_{K+1}\, T_{K+1,K}\, \hat{X}_K\right)$$

where $\hat{X}_K$ is the estimated state vector at time $K\Delta t$; $\hat{X}_{K+1}$, the estimated state vector at time $(K+1)\Delta t$; Z_{K+1}, the measurements at time $(K+1)\Delta t$; H_{K+1}, the observation matrix; and W_{K+1}, the Kalman gain matrix.

The gain matrix, W, is a result of state error propagation which is a function of the plant noise covariance matrix defined as

$$Q_K = \text{Expected Value of } \left(U_K U_K^T\right)$$

Following Singer's derivation,[1] this plant noise covariance has a form when Δt is sufficiently small so that $\alpha\Delta t << \frac{1}{2}$,

$$Q_K = 2\alpha\Delta t\,\sigma_m^2 \begin{bmatrix} \underline{o} & \underline{o} & \underline{o} \\ \underline{o} & \underline{o} & \underline{o} \\ \underline{o} & \underline{o} & \underline{I} \end{bmatrix}$$

where α is related to the maneuver time constant; σ_m^2, the variance of aircraft acceleration; $\underline{o}$, a 3 by 3 zero matrix; and $\underline{I}$, a 3 by 3 identity matrix.

And, $$\sigma_m^2 = \frac{A_{max}^2}{3} F_p\left(P_M, P_Z\right)$$

where A_{max} is the maximum acceleration the aircraft may use; $F_p\,(P_M, P_Z)$, a function of P_M and P_Z; P_M, the probability that the aircraft is flying

[1] Robert A. Singer, "Evaluating Optimal Tracking Filter Performance for Manned Maneuvering Targets," IEEE Trans. Aerospace and Electronic Systems, Vol. AES-6, No. 4, July 1970.

with an acceleration A_{max}; and P_Z, the probability that the aircraft is flying with constant velocity.

It is well known that this plant noise covariance is strongly related to estimation accuracy. For a given maneuvering aircraft and a fixed processing data rate, values of Q_K that are too large will pass excessive measurement noise, and values of Q_K too small will block off the critical information of aircraft maneuvers. Some designers advocate bandwidth adaptation.[2] For this study, the guesses of acceleration probability are adaptive; hence, the variance σ_m^2 is adaptive.

To accomplish this scheme, five intervals of radial acceleration rate are predefined. Five sets of acceleration probabilities corresponding to these intervals are assigned. The average of the previous ten estimates of aircraft acceleration is stored. The rate of change of this average acceleration is tested against the intervals and the acceleration probabilities are updated accordingly. This filter, similar to a hypothesis testing or an adaptive bandwidth filter, has been studied and a report is being prepared to be published soon. The study of this filter has indicated an improvement of about 13 percent in estimation accuracy over that with a fixed value plant noise covariance.

As aircraft state estimates are obtained from this filter, the first and second order predictions are computed by the following equations respectively:

$$\bar{X}_{1ST} = \hat{X}_p + \hat{X}_V t_F$$

$$\bar{X}_{2ND} = \hat{X}_p + \hat{X}_V t_F + \tfrac{1}{2} \hat{X}_a t_F^2$$

where $\hat{X}_p$ is the estimated position vector; $\hat{X}_V$, the estimated velocity vector; $\hat{X}_a$, the estimated acceleration vector; and t_F, the projectile time of flight to intercept which is computed using the estimated states and a projectile flight equation in a performance model.

[2] C. M. Brown, Jr., and C. F. Price, "Adaptive Tracking Filter Design and Evaluation for Gun Fire Control Systems," Reading, MA, The Analytical Science Corporation, January 1974.

III. THE BIAS PREDICTOR

In building a bias predictor, we limited our interest to the following conditions. The target position is known to the fire control. The aircraft will attack the target with a weapon-delivery phase. A nine state Kalman filter will provide the aircraft position, velocity, and acceleration estimates as inputs to this predictor.

The bias predictor performs the following: (1) process the inputs to identify aircraft strategy, (2) set initial and terminal conditions for flying a simulated aircraft, and (3) integrate the simulated aircraft dynamic equations through projectile time of flight.

Processing the inputs is no more than computing the bearing of the aircraft relative to its target, and the initial pitch angle of the aircraft. Assuming the aerodynamic angle of attack to be small, with the information of target position, aircraft position and velocity, the above computation is just simple vector geometry.

To form the rules of the game, an aircraft roll is called for whenever the magnitude of the relative bearing is larger than 2°, and a climb or dive is demanded whenever the pitch angle is greater than 3° or less than -3° respectively. According to these rules, types of aircraft strategy are identified as positive pitch, positive pitch and roll, horizontal flight, horizontal flight and roll, dive, and dive and roll. There is an additional type which is an approximate 180° roll and dive switched from the positive pitch type when the pitch angle is greater than 45°.

The initial conditions are set with the inputs and as functions of type of aircraft strategy. The initial estimated position and velocity, the pitch angle, and the heading angle of the aircraft are given as the inputs or computed directly from the inputs. The acceleration, roll angle, and percentage of power in use are initialized as functions of type of aircraft strategy. Maximum values for acceleration, roll angle, roll rate, rate of acceleration, and rate of power are fixed as functions of type of aircraft strategy also. The initial conditions coincide with the initial estimation of the aircraft state. However, the terminal conditions demand the simulated aircraft to fly a certain bias profile.

The terminal conditions are the following: The commanded pitch angle is a function of aircraft strategy and the initial pitch angle. The attack altitude is a function of aircraft strategy. The commanded velocity is a function of the commanded pitch angle. In the case of the attack heading for the simulated aircraft, a parametric formula was used.

Attack heading = Initial aircraft heading + $(1 + K\frac{V}{V_o})$ * Relative bearing of aircraft and its targets.

where K is an arbitrary constant, V is the estimated speed of the aircraft, and V_o is set to Mach one. The constant K is generally set to 0.3.

An Air Force Model, the Blue Max[3], was used to simulate aircraft aerodynamics. Basically, a set of general point mass force equations is used in a body fixed right-handed coordinate system. The dynamic equations are:

$$\ddot{x} = (T - D - Mg \sin \theta)/M$$

$$\ddot{y} = N \sin \phi / M$$

$$\ddot{z} = (N \cos \phi - Mg \cos \theta)/M$$

where $\ddot{x}$ is the aircraft acceleration along the body axial axis; $\ddot{y}$, that along the horizontal axis; $\ddot{z}$, that along the positive upward axis; T, the thrust exerted on the aircraft; D, the axial drag; N, the normal force; M, the mass of the aircraft; g, the gravitation force constant; θ, the pitch angle; and ϕ, the roll angle. The system is shown in Figure 2.

The driving rate controls of the aircraft have the following forms:

$$p = (h_c - h) - \dot{h}$$

$$\dot{T}_h = (V_c - V) - \dot{V}$$

$$\dot{G} = (\theta_c - \theta) - q$$

where p is the angular roll rate; h, the present heading; h_c, the commanded heading; $\dot{h}$, the heading rate; $\dot{T}_h$, the throttle rate; V, the present speed; V_c, the commanded speed; $\dot{V}$, the rate change of speed; $\dot{G}$, the G-load rate; θ, the pitch angle; θ_c, the commanded pitch angle; and q, the pitch rate.

A power table is provided as a function of altitude and speed of the aircraft for the computation of thrust. A table-look-up procedure is used for computing the normal force as a function of aircraft speed. A drag table is provided as a function of altitude and speed of the aircraft for obtaining the drag force. With these forces and computed pitch

[3] Oleg Komarnitsky and AF/SAFG personnel, "Blue Max," program user's manual, ACS/Studies and Analysis Office, Headquarters USAF, 1974.

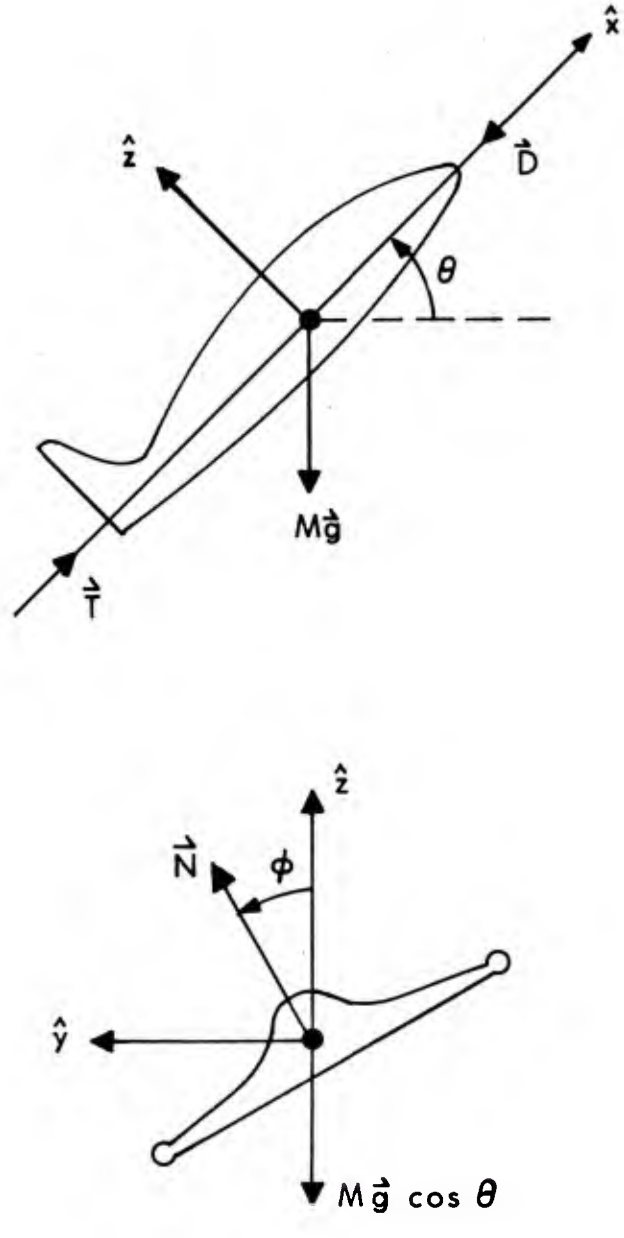

Figure 2. Point Mass Force System for an Aircraft

angle, roll angle, and the aircraft heading, the dynamic equations are integrated through one time step. The process is repeated through the given projectile time of flight. Then, the predicted position of the aircraft from this bias predictor is the actual future position of a simulated aircraft.

IV. THE PERFORMANCE MODEL

To evaluate the performance of this gun fire control system, a modified STAG[4] model was used. Basically, the STAG computes the time of flight of the projectile to intercept, the mean distance at closest approach, and the probability of hit against an aircraft with a burst of n projectiles. The STAG model provides an analytic solution with a single run, but it is not designed to include second order prediction or system lag. Bias and dispersion are taken only root sum square terms from input. To modify the STAG, the probabilities of events were redefined. A new error computation routine was added.

The probability of hit against a diffused target with a burst of n rounds is given as in the STAG model, by

$$P_n = \sum_{j=1}^{n} \binom{n}{j} (-1)^{j+1} \left[\frac{A_V}{2\pi\sigma_D^2 + A_V} \right]^{j-1} \frac{A_V}{2\pi(j\sigma_B^2 + \sigma_D^2) + A_V}$$

$$* e^{-\pi j h^2 / [2\pi(j\sigma_B^2 + \sigma_D^2) + A_V]}$$

where A_V is the projected vulnerable area of the target; h, the mean distance at closest approach; σ_B, the standard deviation of "random" bias; and σ_D, the standard deviation of round to round dispersion.

In general, the miss distance is a function of the estimated states and the prediction algorithm. The errors embedded in the estimated states are system lag, sensor random noise, aircraft glint, and modeling noise or maneuver noise.

In consideration of the randomness of the measurements for a particular flight profile, the average P_n for 20 runs was used as a system performance index. The starting values of the random number generator for

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[4]Fred Bunn, "Surface to Air Gun Model," unpublished study report, Air Warfare Division, AMSAA, APG, MD, 1971.

sensor noise and aircraft glint were different run by run. The error budget used for this performance analysis was based on information from contractors as follows:

Sensor noise, azimuth (1σ)	. . . . .	.00075 radians
	elevation	.00075 radians
	range	3 meters
Aircraft glint, azimuth	. . . .	1 meter
	elevation.	1 meter
Wind, northern	. . . .	5 M/s
eastern	. . . .	5 M/s
Gun recoil, azimuth	. . . .	.0005 radians
	elevation.	.0005 radians
Gun boresight, azimuth	. . . .	.001 radians
	elevation	.001 radians
Sensor misalignment, azimuth	. . . .	.00075 radians
	elevation	.00075 radians
Sensor range bias	. . . .	2 meters
Muzzle velocity variation	. . . . . .	6 M/s
Projectile dispersion, transverse	. .	.001 radians
	elevation . .	.001 radians

An additional factor in the error budget was the artificial dispersion which is mostly a function of range and aircraft acceleration. It may be in the form

$$\sigma_{DA} = \sigma_{DAO} + C \left| \hat{X}_a \right|^2$$

where σ_{DA} is the standard deviation of artificial dispersion; σ_{DAO}, the nonlinear range dependent portion; C, a constant; and $\hat{X}_a$, the estimated acceleration vector.

If the statistics of aircraft maneuvers are completely known to the gun fire control, artificial dispersion is not desirable for an optimal predictor.[5] In the case that neither the statistics of the attacking aircraft maneuvers are completely known, nor the distribution of the aircraft acceleration is exactly Gaussian as modeled, appropriate artificial dispersion often helps improve the system performance. Since the purpose of this study was to examine the possibility of improving system performance by using a bias predictor, optimized artificial dispersion was used. In this context, all predictors in this paper were compared in the upper bound of system performance. It has been found that the optimized dispersion is approximately seven-tenths of the miss distance at closest approach.

With regard to contribution to miss from various error sources, readers are referred to the report by H. K. Weiss.[6] In his report, angular errors due to wind, time of flight variation, and slant range bias are derived. Muzzle velocity variation and head wind give rise to time of flight variation which in turn contributes to angular miss.

With the filter, the predictors, and the performance model, we need a projectile and some flight profiles to play the gun air defense game.

The following values from a typical modern gun system are assumed. Muzzle velocity V_m was set to 1176 meters per second. The drag factor β was set to 0.129. Then, the projectile time of flight

$$t_F = \frac{R}{V_m - \beta R}$$

where R is the intercept range. **Thirty-three rounds per burst was** chosen and the time between burst was 2 seconds. Some flight profiles were selected from the FACTS results. The FACTS data were then processed by least square polynomial curve fitting. Every eleven points were processed to obtain five with a view to maintaining the moderately high frequency component of aircraft motion. The smoothed data were then corrupted by Gaussian noise and fed into the filter.

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[5] Harry L. Reed, Jr., "Some Bounds on the Generalized Fire Control Problem," Report No. 1946, Ballistic Research Laboratory, APG, MD, November, 1976. AD #A033043

[6] H. K. Weiss, "Closed Loop Systems Concept Study," final report, Data Systems Division, Litton Systems, Inc., Van Nuys, CA, September, 1974.

V. RESULTS

For the FACTS flight profile, as shown in Figure 3, miss distance versus target range at intercept for the first order, second order, and bias predictors is shown in Figure 4. The results are summarized in Table 1 and shown in Figure 5.

With the same flight path, except that the fire control was placed 1000 meters cross range in one case, and 2000 meters up range in another case, the results are shown in Figures 6 and 7 respectively.

Results for the profile in Figure 8 are shown in Figures 9 and 10. For the profile in Figure 11, results are shown in Figures 12 and 13.

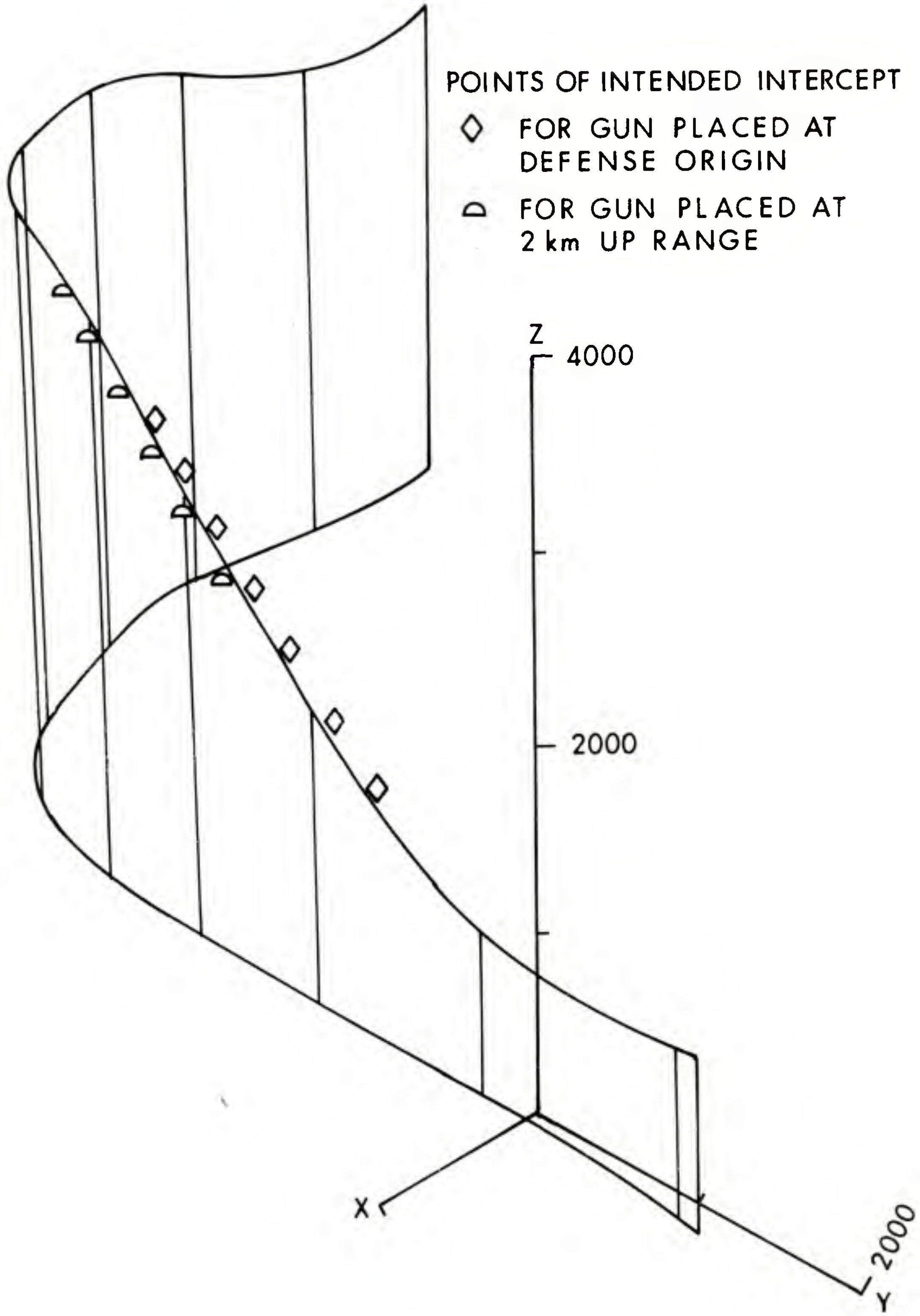

Figure 3. An Aircraft Attacking Flight Profile

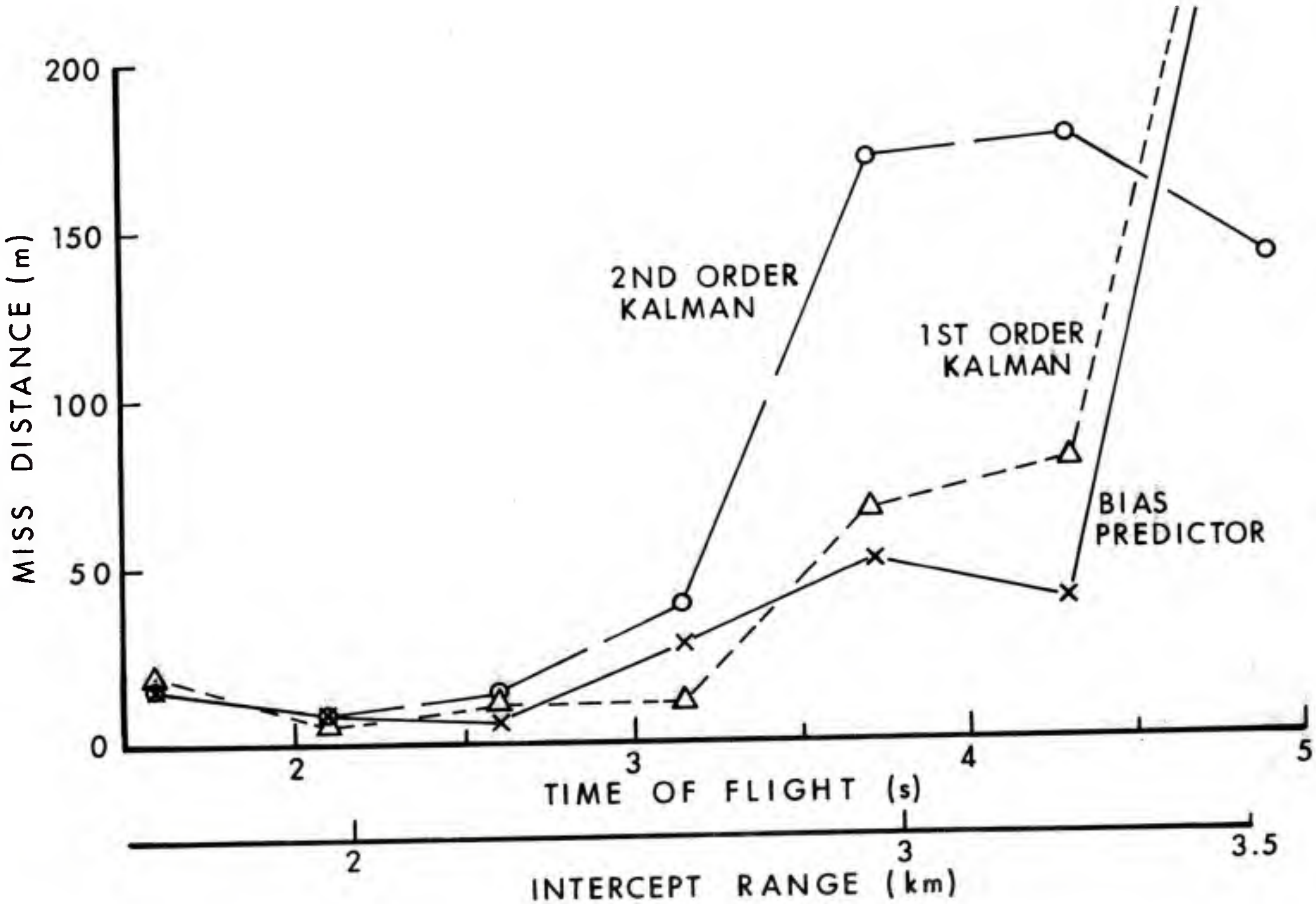

Figure 4. Projectile-Aircraft Miss Distance Against Aircraft Range at Intercept for FACTS Profile as Shown in Figure 3.

TABLE 1. SUMMARIZED PERFORMANCE OF SYSTEMS WITH DIFFERENT PREDICTORS FOR FLIGHT PROFILE AS SHOWN IN FIGURE 3

POINT OF INTERCEPT	1	2	3	4	5	6	7	AVERAGE
APPROXIMATE INT. RANGE(m)	3535	3257	2962	2646	2307	1949	1571	
APPROXIMATE TIME OF FLIGHT (s)	4.909	4.310	3.732	3.170	2.626	2.108	1.614	
MISS DISTANCE (m)								
1st Order	321.4	82.9	68.0	11.7	9.8	5.5	19.2	
2nd Order	142.3	178.5	170.9	30.5	14.4	8.0	16.5	
Bias Pred.	309.8	40.7	52.8	28.6	7.3	7.8	15.7	
PROBABILITY OF SINGLE SHOT HIT								
1st Order	.0000	.0001	.0001	.0050	.0094	.0208	.0030	
2nd Order	.0001	.0000	.0000	.0012	.0067	.0139	.0043	
Bias Pred.	.0000	.0005	.0002	.0012	.0159	.0187	.0050	
PROBABILITY OF BURST HIT (33 Rounds)								
1st Order	.0003	.0026	.0031	.1512	.2677	.5005	.0933	.146
2nd Order	.0033	.0005	.0005	.0399	.1992	.3709	.1340	.107
Bias Pred.	.0002	.0155	.0056	.0393	.4102	.4628	.1526	.155

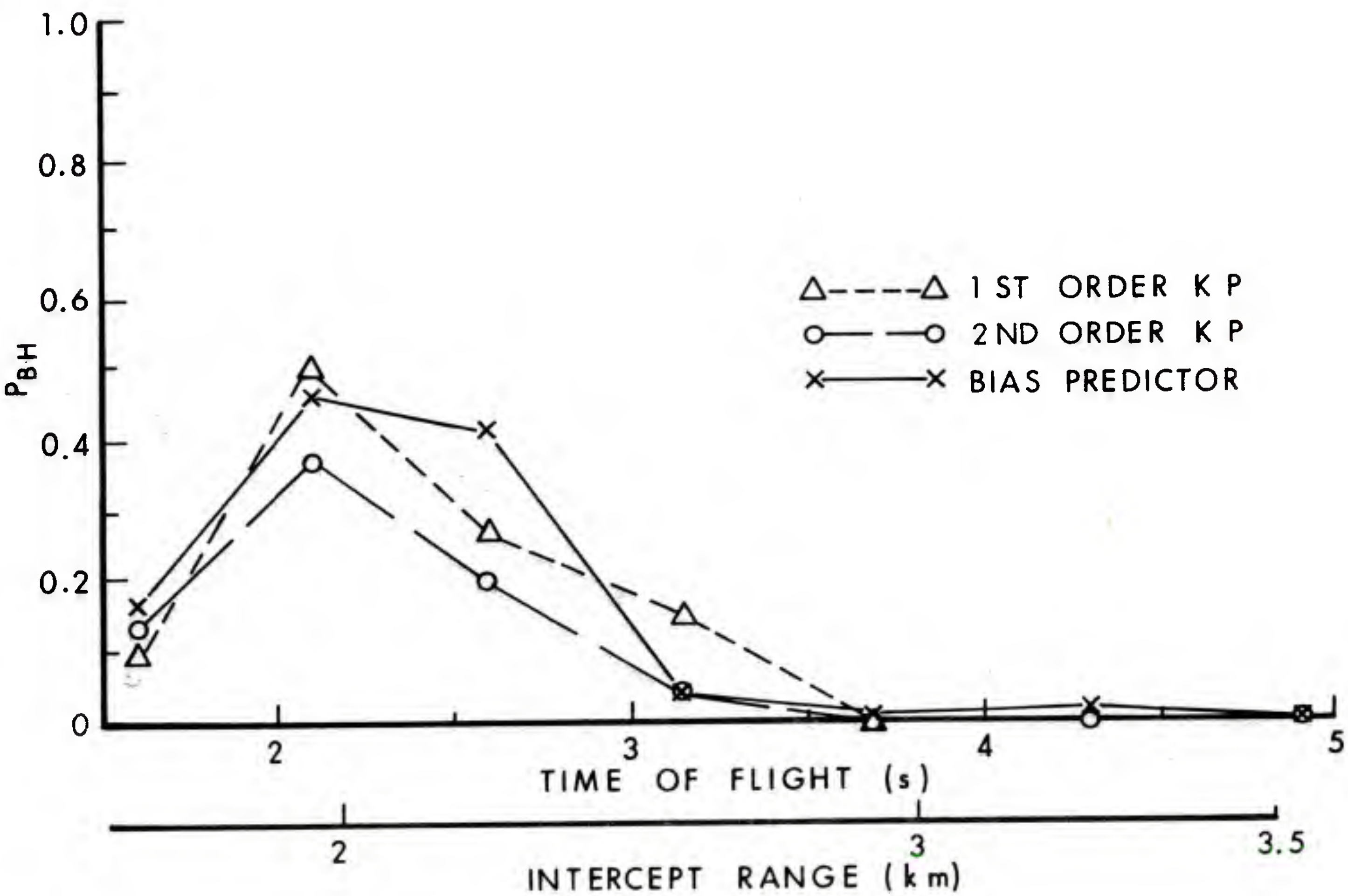

Figure 5. Probability of Hit per Burst (33 Rounds) With Gun at Origin in FACTS Profile as Shown in Figure 3.

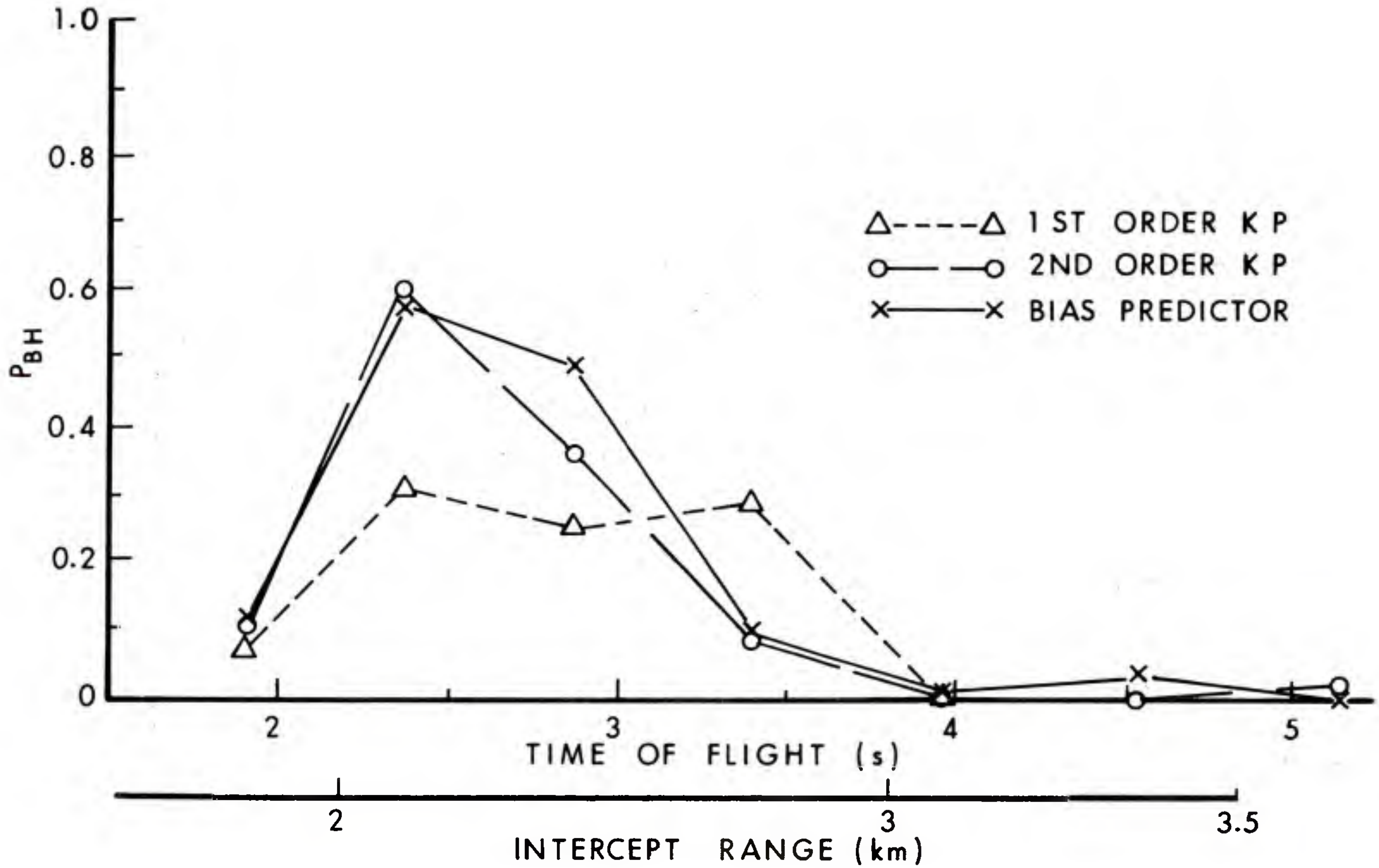

Figure 6. Probability of Hit per Burst (33 Rounds) With Gun Displaced by 1 km Cross Range in FACTS Profile as Shown in Figure 3.

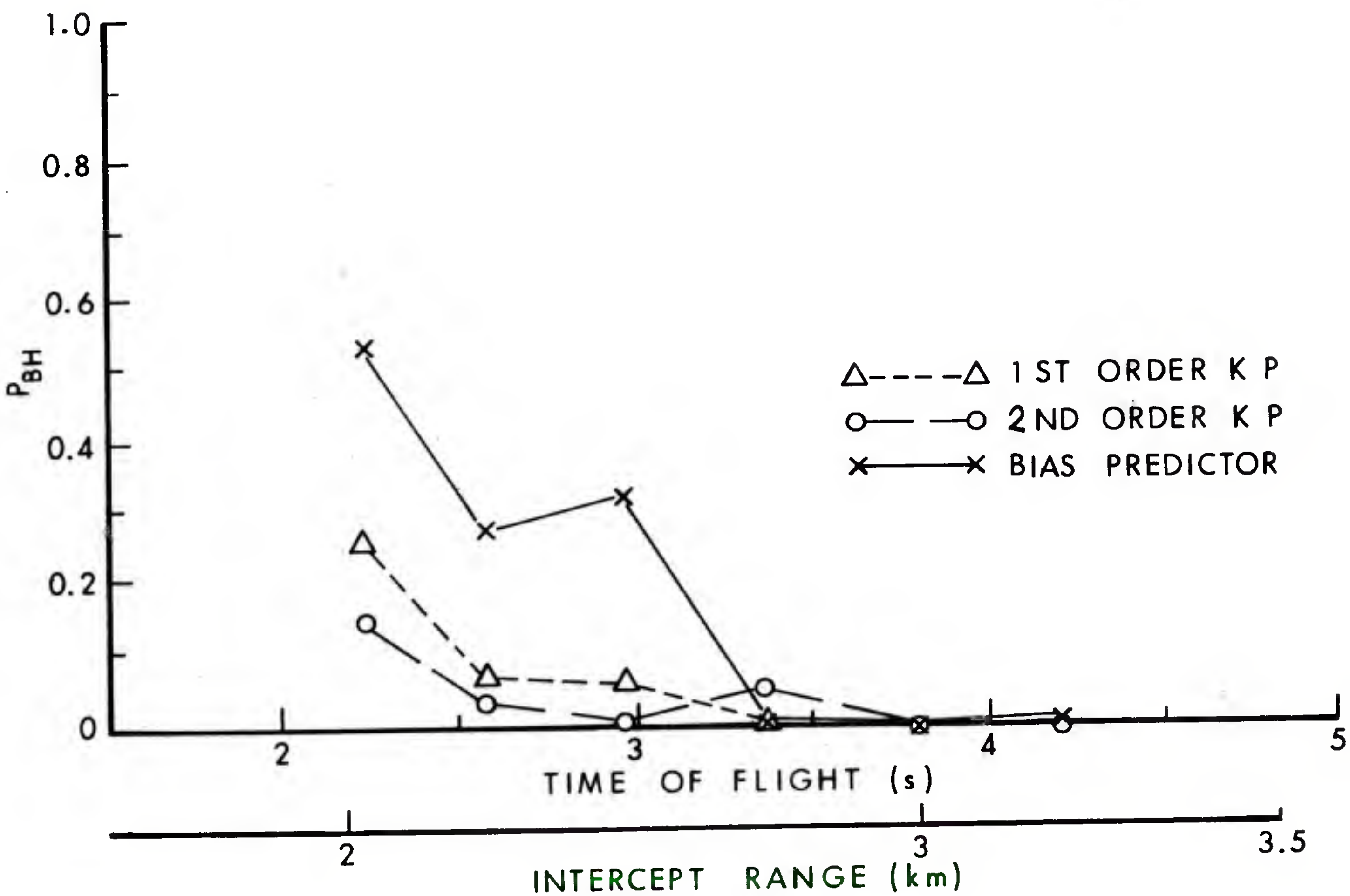

Figure 7. Probability of Hit per Burst (33 Rounds) with Gun Displaced by 2 km Up Range in FACTS Profile as Shown in Figure 3.

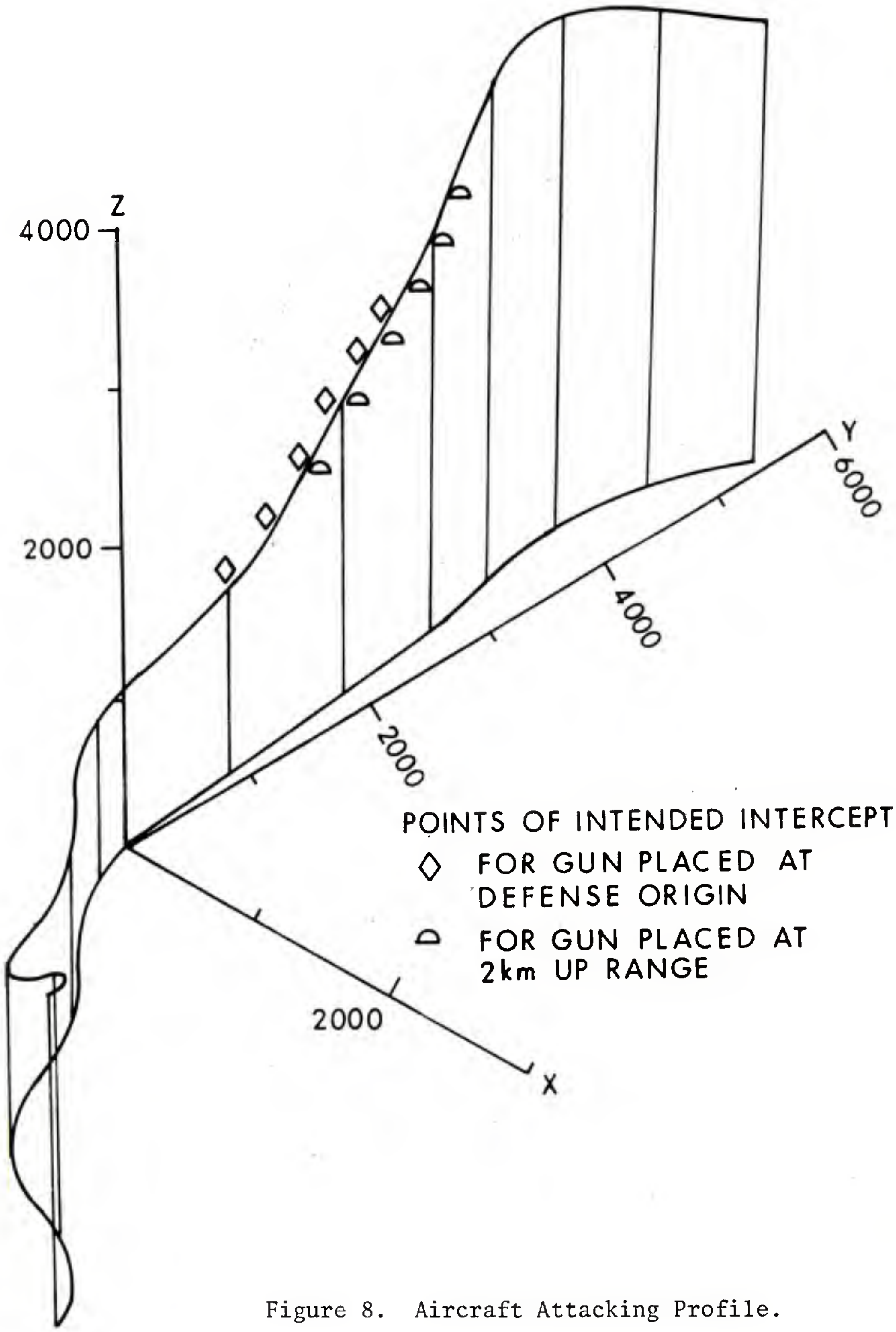

Figure 8. Aircraft Attacking Profile.

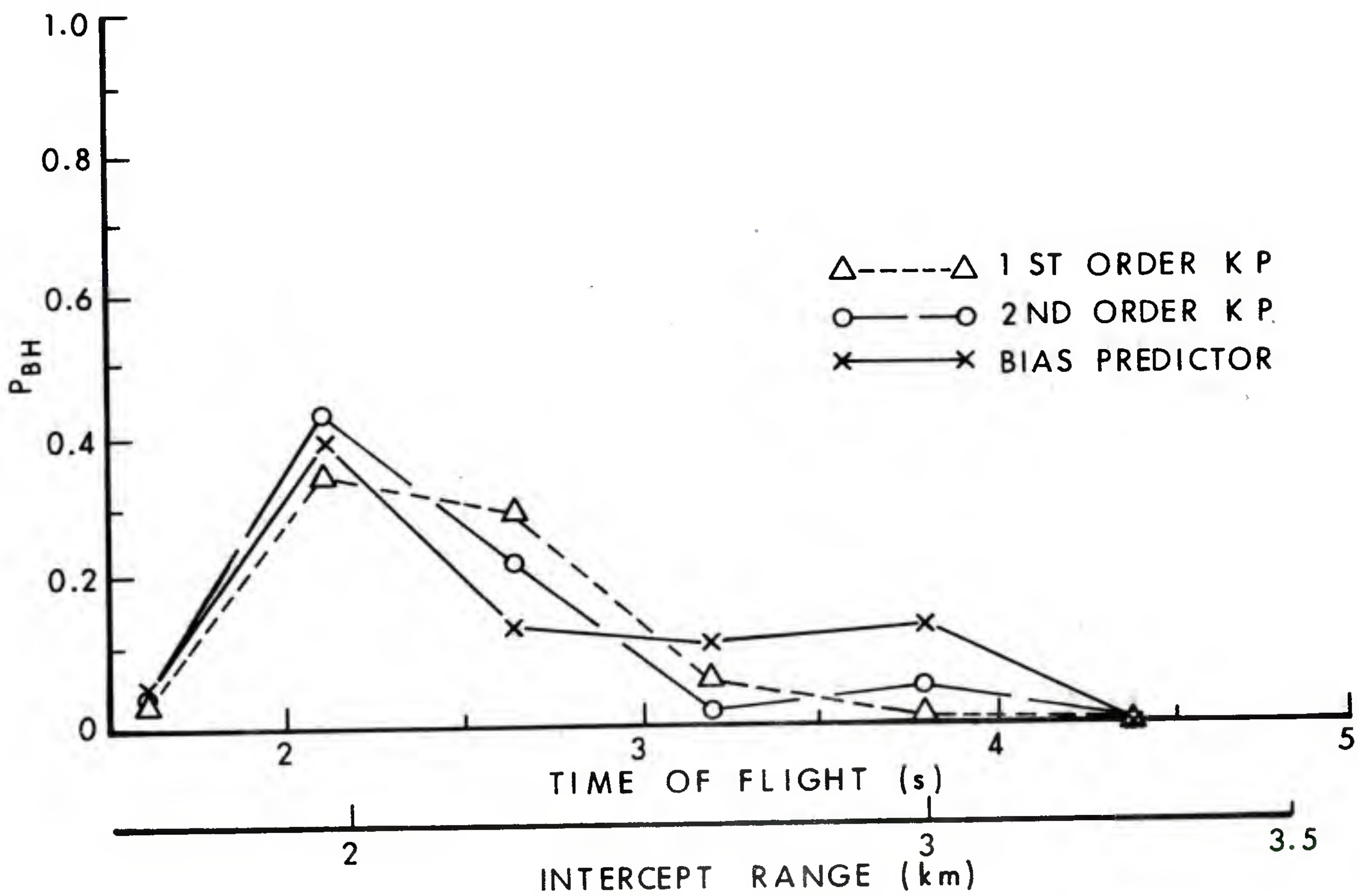

Figure 9. Probability of Hit per Burst (33 Rounds) With Gun at Origin in FACTS Profile as Shown in Figure 8.

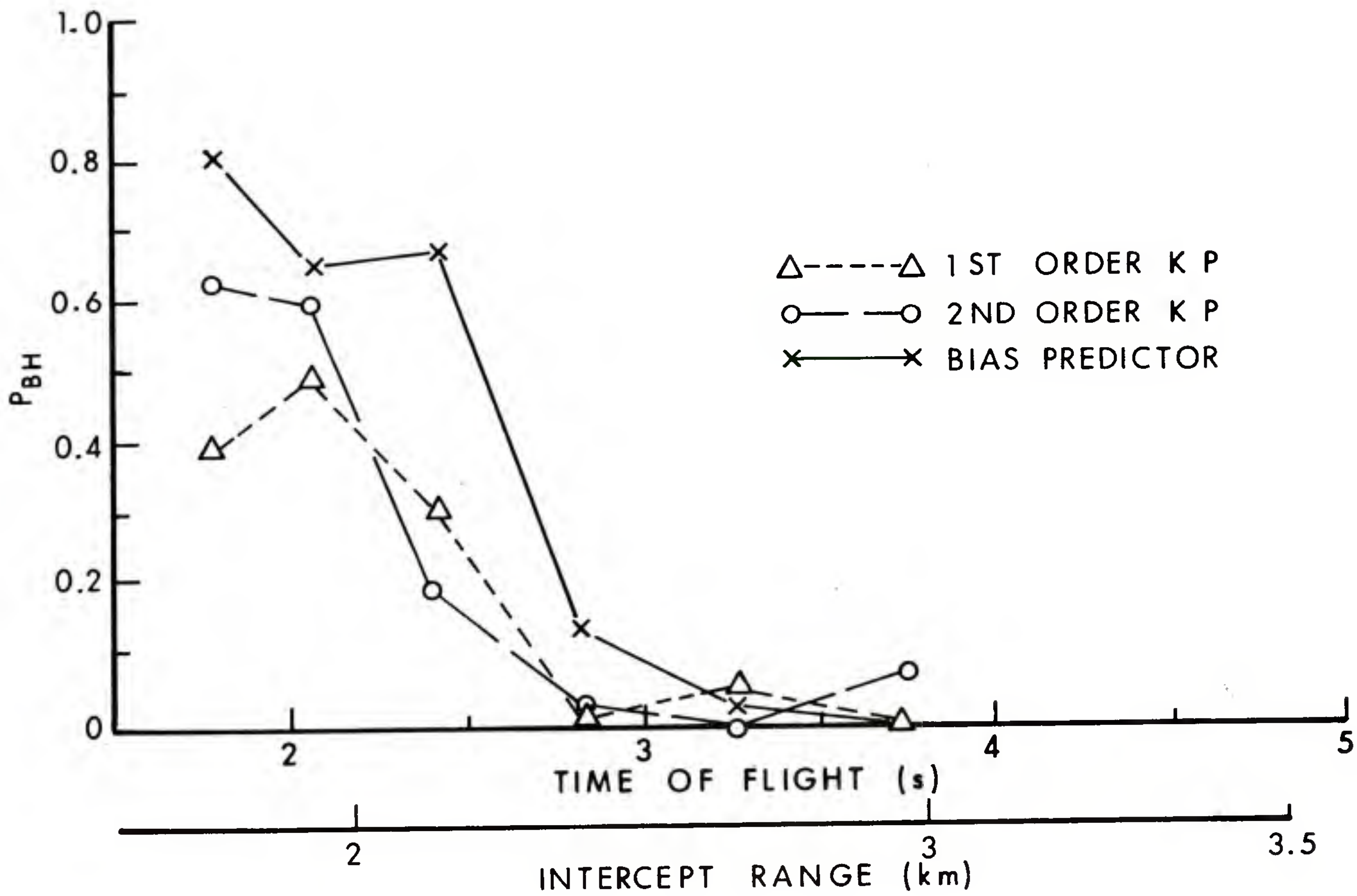

Figure 10. Probability of Hit per Burst (33 Rounds) With Gun Displaced by 2 km Up Range in FACTS Profile as Shown in Figure 8.

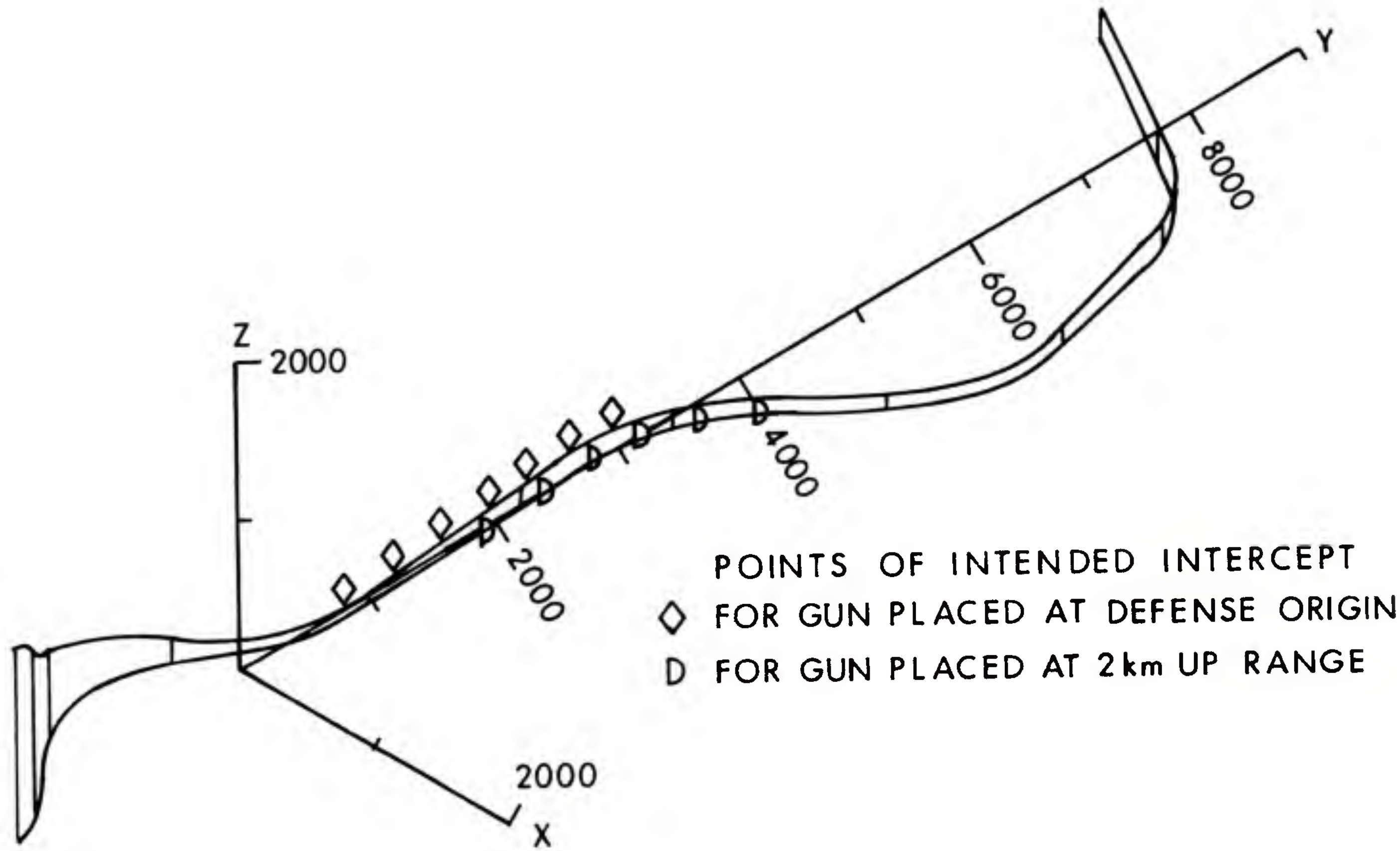

Figure 11. Aircraft Attacking Profile.

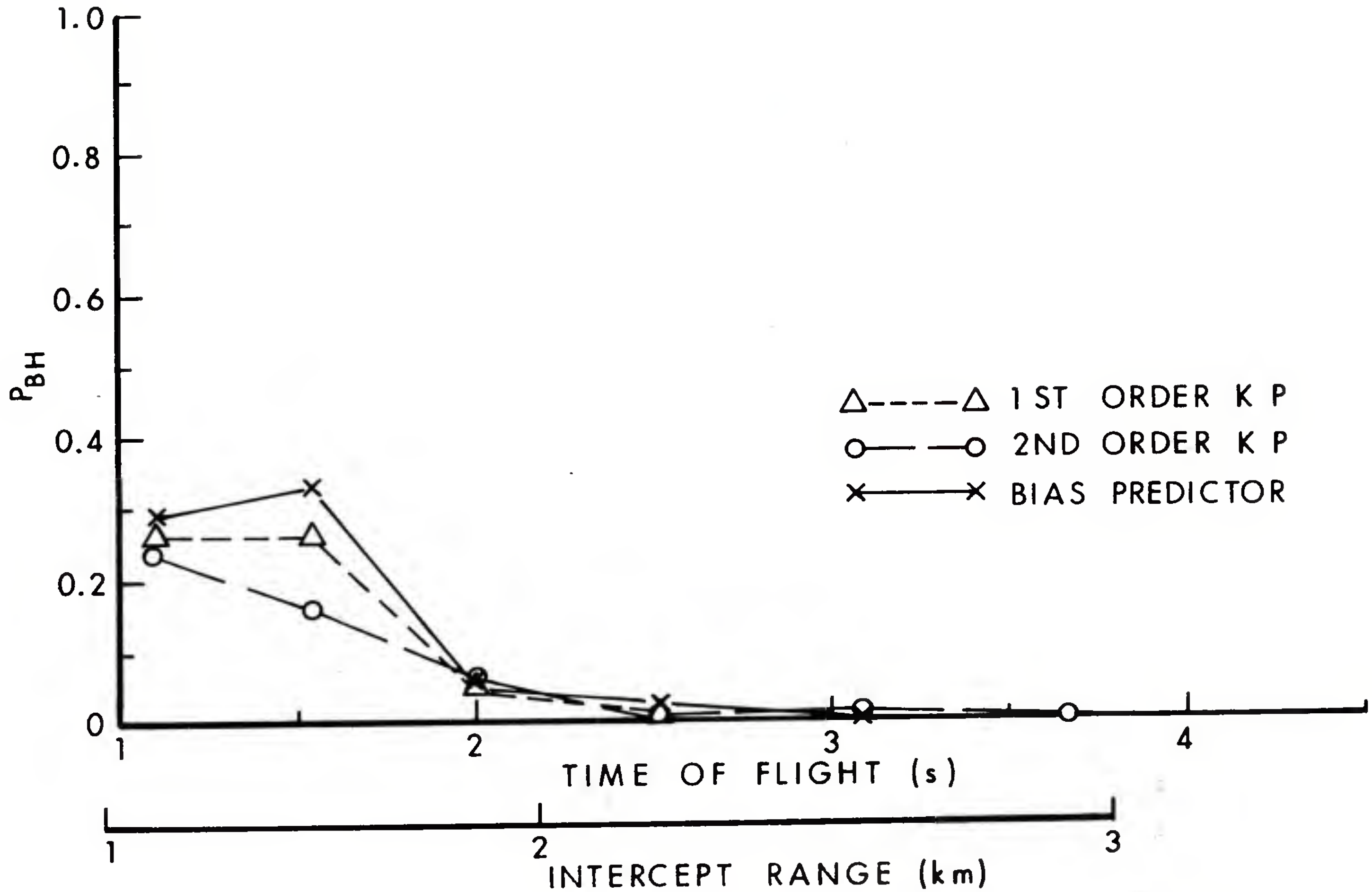

Figure 12. Probability of Hit per Burst (33 Rounds) With Gun at Origin in FACTS Profile as Shown in Figure 11.

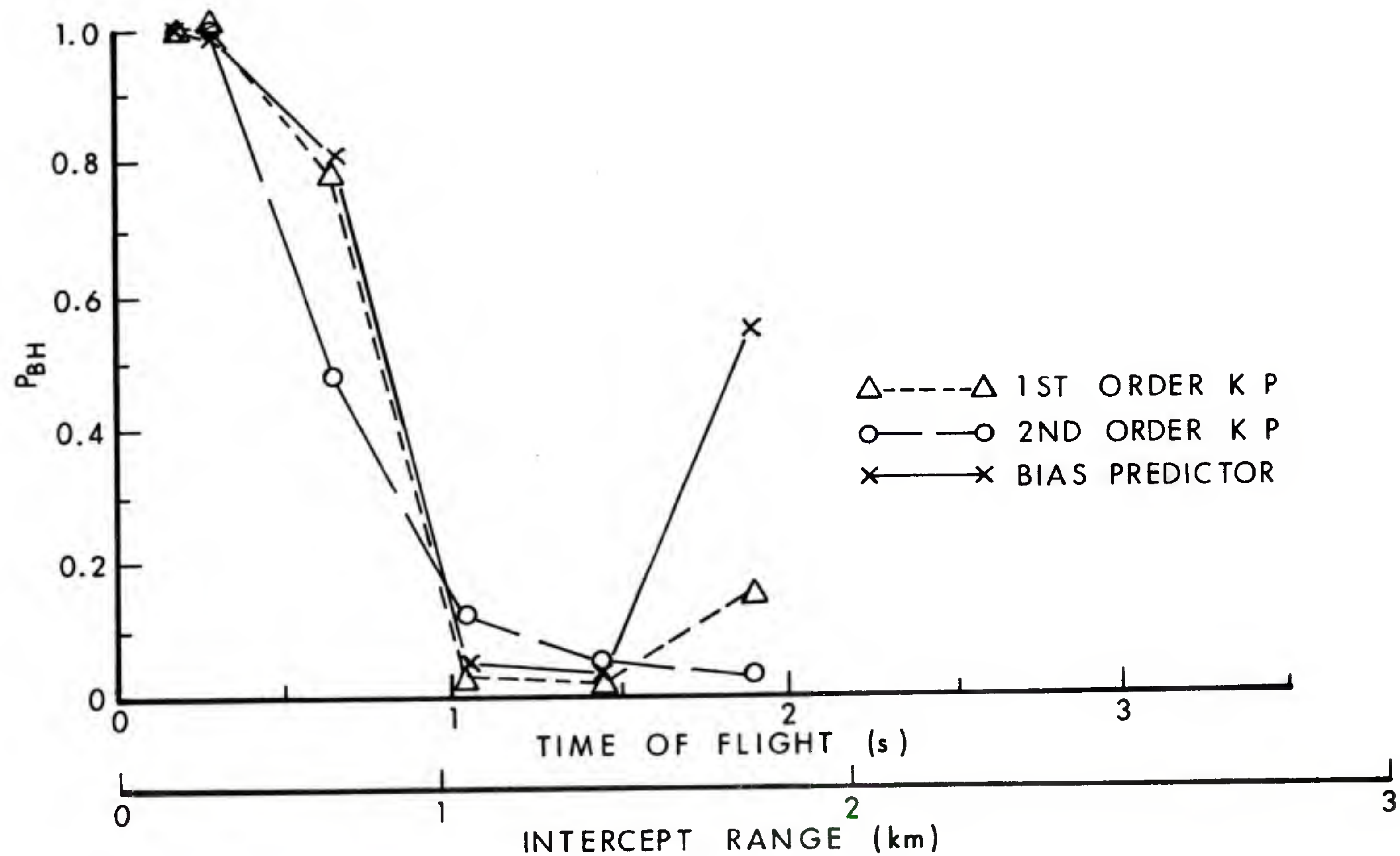

Figure 13. Probability of Hit per Burst (33 Rounds) With Gun Displaced by 2 km Up Range in FACTS Profile as Shown in Figure 11.

VI. DISCUSSION

In general, a Kalman filter is always included in the design of modern gun fire control systems. Since an attacking aircraft has a large spectrum of possible acceleration rates, the Kalman prediction has certain disadvantages. In the case of the second order prediction, very little accuracy can be obtained in the beginning stage of the weapon-delivery phase because the filter requires approximately 3 seconds to settle its acceleration states from high maneuver to very low maneuver at ranges beyond 3 kilometers. Also, for the relative slight maneuvers in this phase, the processing of acceleration noise by the filter will result in an increase in the prediction error. Therefore, in this case, the second order prediction will be inferior to the first order prediction. In the case of the first order prediction, about one second is required for the velocity term to settle for the same transition of maneuver. Moreover, if the flight profile is a dive with an attack elevation angle, prediction errors may be increased due to neglecting the gravitational pull on the aircraft.

In this study, it has been demonstrated that, if the aircraft actually attacks a target, the position of which is known, a bias prediction algorithm provides better state predictions in the weapon-delivery phase. This predictor becomes effective as soon as reasonable position estimates are obtained. The bias predictor model describes the aircraft profile more accurately in lay down or delivery dive because the flight is aerodynamically simulated. However, this bias predictor adds a considerable burden to the fire control computer.

As now there are still great difficulties in providing accurate estimation of aircraft states in the pre-delivery-maneuver phase in the attacking aircraft strategy. No known air defense fire control algorithm is adequate for this task, yet, as aircraft fire control systems become more sophisticated, their capability for delivery of ordnance at greater ranges and maneuver conditions will also increase. It is this unresolved problem that creates the challenge for further research effort. Therefore, our next study will be addressed to using an aircraft model with identified sets of aerodynamic characteristics of corresponding aircraft to predict projectile-aircraft intercept in the pre-delivery-maneuver phase.

To predict the future position of an aircraft is never an easy task, since behind the aircraft a human decision is involved. Improvement of system performance has come from advanced sensors, high velocity projectiles, better filters and better gun systems. Perhaps switching of predictors for the different phases of an attacking flight profile may join the march on the road with the rest to a better solution for the gun air defense problem.

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